Tree growth and hydrologic patterns in urban forested mitigation wetlands

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Abstract

Tree growth and hydrologic patterns in three forested mitigation wetlands in urban Central Ohio were compared with those in a nearby reference forested wetland and with previous data collected at these wetlands. In two mitigation wetlands, trees had been planted around deepwater basins, while the other two wetlands, including a reference wetland, had established forests around vernal pools. Hydroperiod and precipitation data were used to quantify aspects of the hydrology in the planted wetlands. The two planted sites received their primary water sources from streams but their hydrographs were decidedly different. Tree growth, survival and recruitment data were used to assess the persistence of the trees and their productivity and to validate a previously created tree growth model. Trees at the planted sites had significantly higher annual growth than the established sites. However, the established forest sites had significantly larger trees and, as a result, significantly higher annual basal area growth than the planted sites. Total basal area of the reference site was 38 m^2/ha compared to 2 m^2/ha at the planted sites. Tree diversity and species richness were higher at the reference site (H' = 2.7, richness = 29) than at the planted sites which averaged H' = 2.05 and richness = 12.5. The established sites, with larger and flood tolerant trees at lower elevations, exhibited greater growth there, while the planted sites showed the highest growth at mid-elevations. Of the planted trees, *Fraxinus pennsylvanica* exhibited the greatest annual radial growth and basal growth at 0.9 cm/yr and 11.5 cm^2/yr, respectively. The most dominant species at the planted sites was *Acer saccharinum* and a tree growth model predicted its growth within 10%. Using this model it was estimated that *Acer saccharinum* trees would need 44 years to meet the reference site's average DBH. *Quercus palustris* was the planted species with the lowest mortality at both sites. Volunteer trees made up 60% of the trees at the planted sites. Planting did enhance the establishment of a forest as the mean DBH of planted *Fraxinus pennsylvanica* was 13.0 cm while volunteer tree mean DBH was 2.6 cm. The three created sites each illustrated a property that enhanced tree growth, density or productivity. The site with the greatest hydrologic pulsing produced the greatest growth in DBH/yr; the site closest to an existing bottomland forest had the greatest tree density and volunteer tree DBH and height; and the site created in an existing forest generated the highest basal area increase per year.

Introduction

Wetlands that are created or restored to mitigate the loss of other wetlands often are not successful because proper hydrologic conditions have not been established (Morgan and Roberts, 2003). This is particularly true when wetlands are created for mitigation of forested wetland loss. In the U.S., the greatest losses of wetlands from 1950 to 1980 were in freshwater forested wetlands (Frayer et al., 1983) although recent evidence has suggested that this trend has stopped in the USA (Dahl, 2006). Forested wetlands take decades to develop, as was illustrated when a tree growth model estimated it could take 50 years for a tree-planted migration site to reach the basal area of a natural forested wetland (Niswander and Mitsch, 1995).

Knowing what factors maximize tree growth and persistence can shorten the time to reach wetland creation project goals (Wallace et al., 1996) Hydrology is the most important factor influencing forested wetland productivity (Conner, 1994; Mitsch and Gosselink, 2000), affecting soil aeration, nutrient availability, and vegetation survival. The frequency and duration of inundation depends on the elevation of the land (Gosselink et al., 1981), as well as climate and soils. The duration, depth and timing of flooding affects tree growth, mortality, distribution and species composition within sites (Dudek et al., 1998; Kozlowski, 1979; McKnight et al., 1981; Megonigal et al., 1997; Mitsch and Ewel, 1979; Mitsch and Rust, 1984; Teskey and Hinckley, 1977).

When the water table is present in the root zone, the effects can be both beneficial and detrimental on tree growth (Spurr and Barnes, 1973). Prolonged surface flooding, where water remains throughout the growing season, usually has a harmful effect on tree growth and survival. Lack of oxygen to roots for respiration causes damage, which increases with flooding duration. Season of flooding has an effect as there is more oxygen dissolved in cold water and dormant plant roots require less oxygen (Broadfoot and Williston, 1973). Most tree seedlings die back to the ground if flooded more than 2 weeks after they have leafed out, but may resprout when the waters recede. Deposition of sediment from flood waters can damage trees if three or more inches smother the roots. Floods can enhance growth by bringing in nutrients-enriched sediments and additional water for transpiration. Chemical changes in flooded soil may make some micronutrients more available (Mitsch and Rust, 1984).

The goal of this study was to investigate and predict the long-term success of urban forested wetland creation to mitigate the loss of forested wetlands. The specific objectives to meet these goals are to:

1. evaluate wetland tree productivity and persistence over time using tree growth and survival estimates at selected mitigation sites; and
2. quantify the wetland hydrology at the planted sites.

Methods

Site descriptions

All of the forested wetland study sites are in the eastern half of Franklin County, Ohio, in or near Columbus, and are all located in the Upper Scioto watershed (Figure 1). Table 1 describes the wetlands as mitigation or reference, if they were planted with trees or already had an established forest.

Blacklick Creek mitigation wetland is a 34.3 ha site located in Groveport (latitude 39° 52' 33.3" longitude 82° 53' 27.1") (Figure 2a). The wetland was created to compensate for impacts to 10 ha of wetlands in Dublin, Ohio. The mitigation, begun in 1994, included excavation of a pond with channels from and back to Blacklick Creek. The site was designed to be a surface-water driven system with water sources from precipitation, runoff, and flooding of Blacklick Creek. Thirteen-thousand trees were planted on 18 ha of the site in the spring of 1994.

New Albany mitigation wetland is a 16 ha site adjacent to

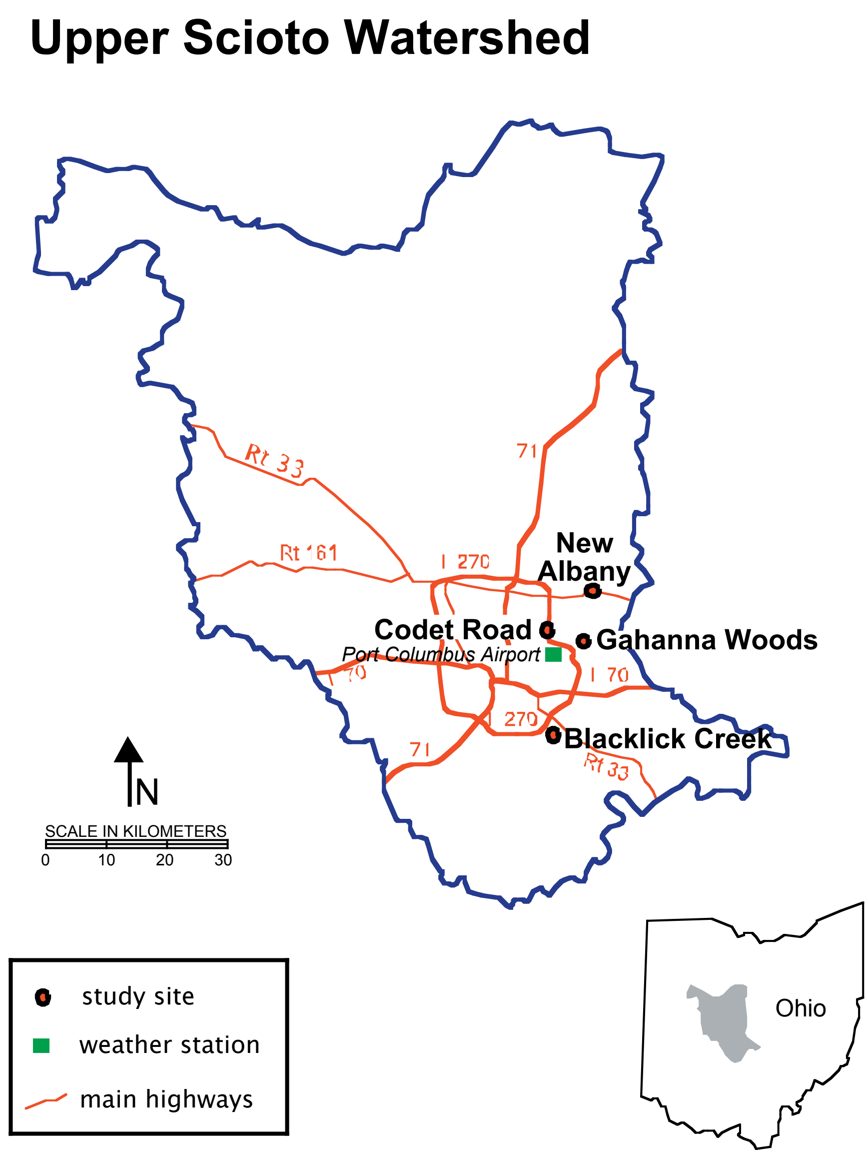


Figure 1 Upper Scioto River watershed in Ohio showing locations of each wetland in this study and the location of the Port Columbus Airport where precipitation data were obtained.

Table 1 Comparisons of the four wetlands used in this study based on type of mitigation, whether site has planted or existing forest, year construction completed, and whether site has vernal pools or larger basins.

Site	Mitigation strategy	Forest type	Year construction ended	Vernal pools?	Deepwater ponds?
Blacklick Creek	Created	Planted	1994	No	Yes
Codet Road	Created	Planted	1992	No	Yes
New Albany	Created & restored	Established	1996	Yes	Yes, but not studied
Gahanna Woods	(Reference)	Established	NA	Yes	No

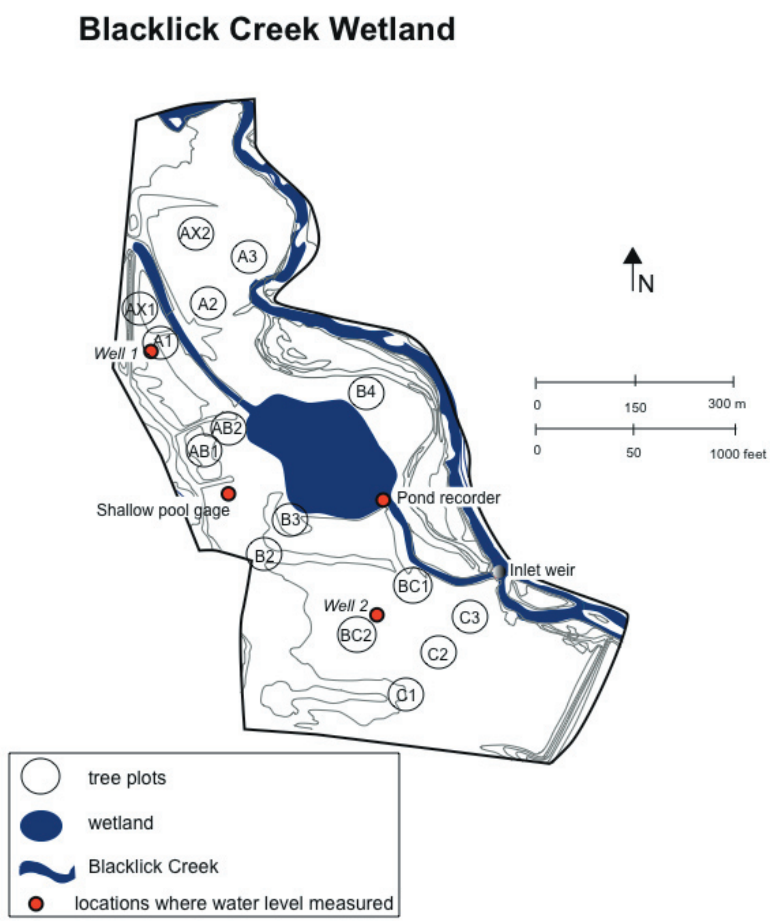


Figure 2a Site map Blacklick Creek mitigation wetland showing locations of inlet from Blacklick Creek, pond recorder and shallow pool staff gage, tree plots, and groundwater monitoring wells.

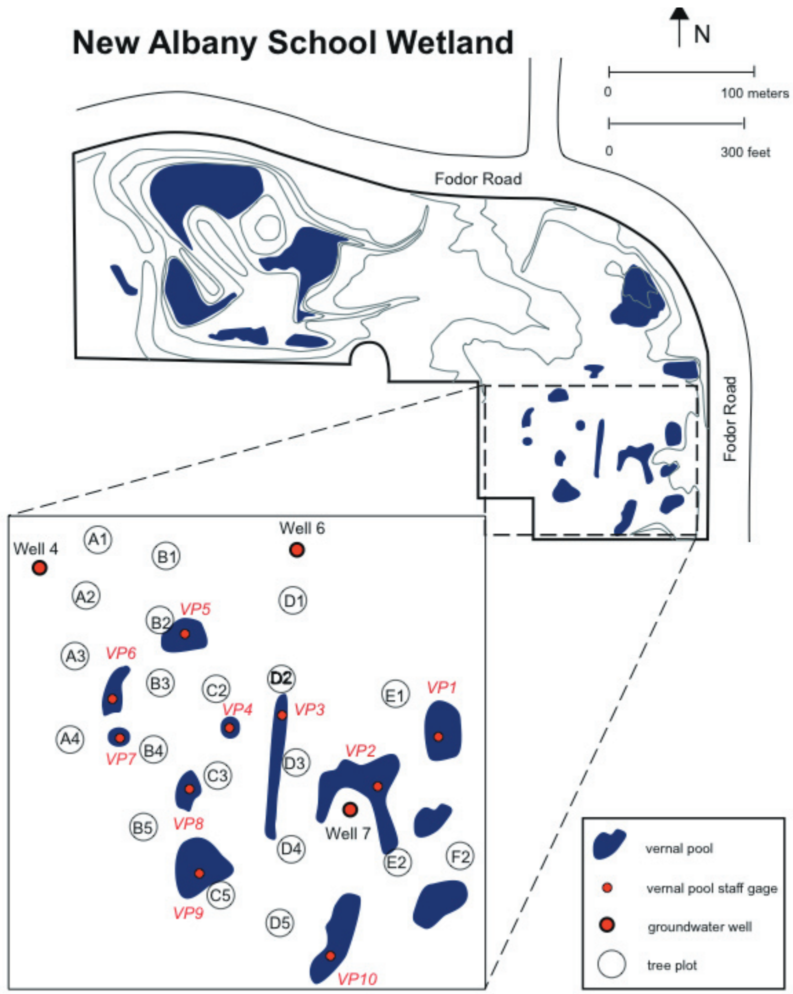


Figure 2b Site map for New Albany mitigation wetland showing location of vernal pools 1 through 10, groundwater monitoring wells, and tree plot locations.

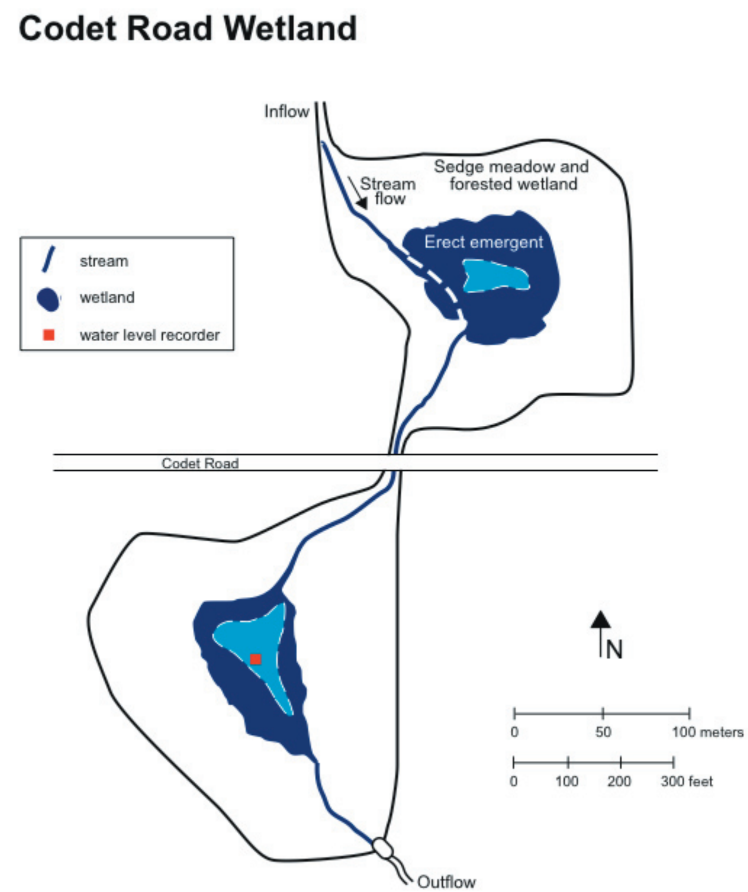


Figure 2c Site map for Codet Road mitigation wetland showing location of south basin water level recorder, inflow in north basin, and outflow in south basin.

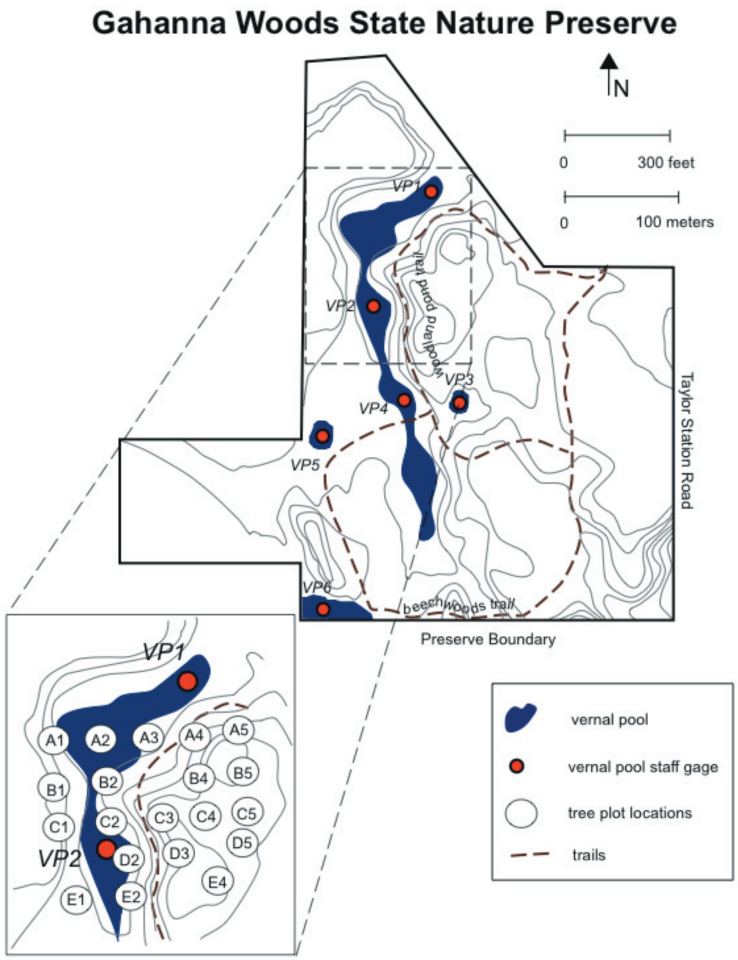


Figure 2d Site map for Gahanna Woods State Nature Preserve showing locations of vernal pools 1 through 6 and tree plot locations.

the High and Middle Schools in New Albany (Latitude 40° 05' 09.3", Longitude 82° 49' 10.7") (Figure 2b). Construction was completed in 1996 to compensate for impacts to 10 ha of palustrine emergent, palustrine open water and palustrine-forested wetlands destroyed in the relocation and widening of a state highway. No trees were planted at this site, as a well-developed forest already existed there.

The Codet Road mitigation wetland (Figure 2c) is on a 6.1 ha site located on Codet Road, 3 km north of the Columbus International Airport (Latitude 40° 01' 29.6", Longitude 82° 54' 25.1"). Construction on the site was completed in 1992 to mitigate the loss of 3 ha of wetlands located in corn/soybean fields and along a stream immediately north of the site for the construction of a new research park for Ross Labs, Inc. The mitigation site, designed to be an in-stream forested wetland, consists of two basins with a channelized stream diverted to flow through them, with an outflow weir regulating water depth (Niswander and Mitsch, 1995). Over 800 trees were planted at the site in the fall of 1991.

Gahanna Woods, a 23-ha nature preserve located in Gahanna (Latitude 40° 00' 35.5", Longitude 82° 50' 14.9") (Figure 2d), was our reference site. The preserve includes buttonbush swamps and vernal pools surrounded by pin oak-silver maple swamp forest and mature oak-hickory and beech maple forest on uplands.

Precipitation and stage levels

Precipitation data for all sites were obtained from the Columbus International Airport weather station (location in Fig. 1). Stage levels for Codet Road and Blacklick Creek were obtained from Steven's water level recorders installed on stilling pipes in the pond at the Blacklick Creek site on 9 April 2004 and in the south basin of the Codet Road site on 27 March 2004 (Fig, 2a, c).

Elevations were determined for water level recorders using a Topcon Positioning Systems, Inc. Model RL-H3C Laser Level.

Tree growth and diversity

Tree size was measured in selected plots in 2005 at all 4

Table 2 Trees measured at the 4 wetlands (trees >1.3 m tall.) Plots were created in 2004 and revisited in 2005 to determine growth in one year for Gahanna Woods and New Albany. Tree data were previously reported in 1998 for Blacklick Creek and in 1992 for Codet Road and the same plots were revisited in 2005 to determine growth since then. Superscripts beside values indicate statistically significant differences.

Wetland	# trees measured measured	Total area measured (ha)	Density of trees (trees/ha)	Total basal area/ha in 2005 (m^2/ha)	Mean tree dbh in 2005 (cm)
Gahanna Woods	701	0.81	567	38.2	15.2 ± 0.7a
New Albany	543	0.81	440	22.8	14.9 ± 0.6a
Blacklick Creek	312	0.61	511	1.7	5.1 ± 0.3 (planted) ^{b} 5.8 ± 0.2 (all)
Codet Road	325	0.94	345	2.0	9.5 ± 0.4 (planted) ^{b} 7.3 ± 0.3 (all)
All	1881	3.17	593	16.5	13.6 ± 0.4

sites and either compared to measurements from the same trees in 2004 (Gahanna Woods and New Albany) or with data from previous studies (Codet Road and Blacklick Creek). Only trees ≥ 1.3 m in height and ≥ 2.25 cm in diameter were used in this comparison.

For each tree in a plot, the species was recorded, the diameter at breast height (DBH = 1.3 m) was measured using measuring tape or calipers; the general condition of the tree was noted , and the location was georeferenced using a Garmin model 12XL GPS unit (Garmin Corporation, Olathe, KS). If the tree had a swelling or branch at a height of 1.3 m, diameter was measured at a height where the stem appeared normal. If a tree forked below 1.3 m, only the thickest trunk was measured. Ground elevations were measured using the laser level at the center stake in circular plots or within the plot area in square plots. At the planted tree sites, tree height was measured using a stadia rod or a clinometer.

At the Codet Road site, tree growth was assessed by recreating the grid consisting of 140-10 m x 10 m plots from a 1992 study (Niswander and Mitsch 1995), identifying tree species within those plots and recording their DBH and height. Tree measurements taken in 2005 were compared with measurements taken in 1992. Tree volunteering (>1.3m in height) since that time were also measured and noted.

At Blacklick Creek, tree species and survival was compared to 1998 data (LAW Engineering and Environmental Services, 1998) from 24 0.04 ha circular plots. Only 15 of the 24 original plot center stakes were located, so these 15 plots were sampled. Data from volunteer trees were also recorded. Because diameters of the trees planted in 1994 were not recorded in the 1998 report, the DBH and height in 1994 were estimated from photographs of the site from that time.

Trees at New Albany and Gahanna Woods were not measured previously and had no existing plots. Circular 0.04 ha (11.3-m radius) plots were set up so the same trees were remeasured the 2nd year, resulting in a smaller error. At these sites, a grid of 25 plots was set up with centers of the plots being 24.4 m away from each other to subdivide the vernal pool region into homogeneous areas. At Gahanna Woods, the plots were set up in the least disturbed central core area (Fineran, 1999). Twenty plots were needed to estimate the population mean within ± 10 percent at a probability level of 0.95 (Avery and Burkhart, 1983). These 20 plots were randomly selected from the grid. If a plot fell more than 50% within a vernal pool, the next available plot was used. Each tree in a selected plot was marked with a wax-type marker at 1.3m above the ground the first year and tagged with an aluminum tags etched with the plot and tree number.

Tree growth was statistically compared using t-tests and ANOVA with Tukey's method of multiple comparisons. Analyses were conducted using Minitab for Windows statistical software, version 12.21 by Minitab Inc.

Tree species diversity was calculated for each site using the Shannon-Wiener function (MacArthur and MacArthur, 1961). Counts of individuals were standardized to number of individuals/ha.

Tree growth model

Simulated tree DBH from the Niswander and Mitsch (1995) tree growth model were compared to field measured tree DBH in 2005 for the Codet Road site. Tree heights calculated from the Botkin (1993) equation were compared to field measured tree heights from Codet Road.

Results

Tree growth by site

The greatest annual growth in DBH occurred at the two planted sites, Codet Road and Blacklick Creek (Figure 3a), with Codet Road being significantly higher than all the

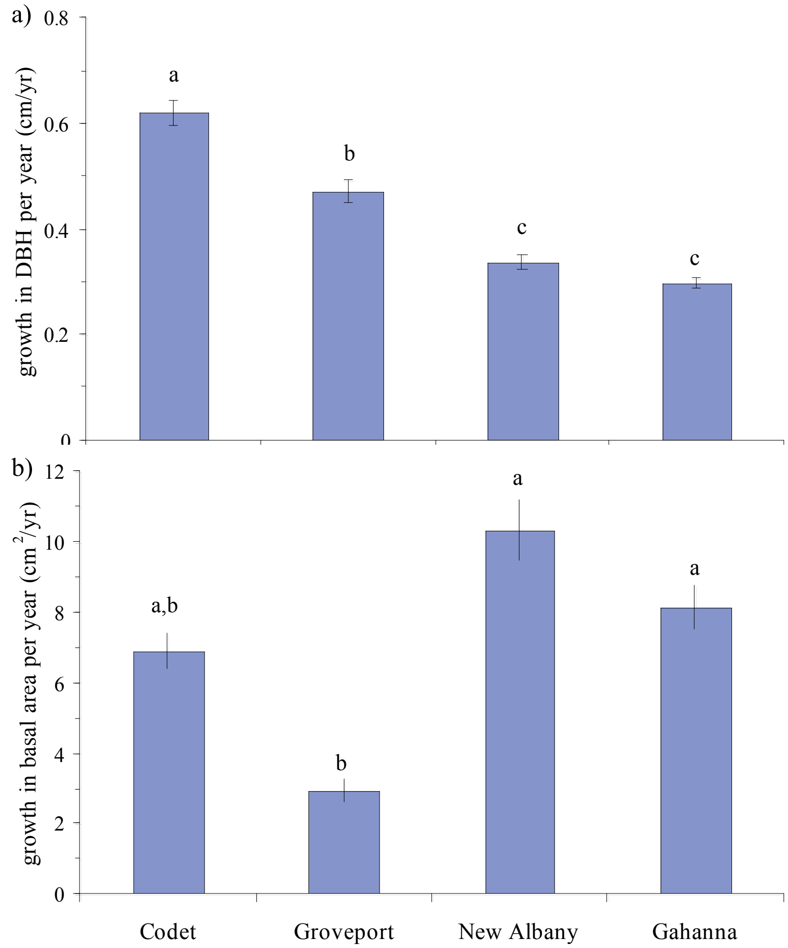


Figure 3 Comparison of a) annual growth in DBH and b) annual growth in basal area among wetlands. A change in letter above the bar indicates statistically-significant differences.

other sites. Blacklick Creek was only significantly higher than Gahanna (ANOVA, □=0.05, p<0.000). Conversely, both the established forest sites, New Albany and Gahanna Woods, had significantly greater growth in basal area/yr than Blacklick Creek (ANOVA, □=0.05, p<0.000) (Figure 3b). Codet Road's basal area increase was not significantly different from any other site. The established forests had greater tree diameters, averaging around 15 cm DBH (ANOVA, □=0.05, p<0.000) (Table 2) and therefore greater basal area growth. Codet Road's planted trees averaged 9.5 cm DBH while trees at Blacklick Creek, planted 2 years later, averaged 5.1 cm DBH. Gahanna Woods, the reference site with mature trees, had the greatest density and total basal area. There was no significant difference in growth in DBH/yr, basal area/yr, total basal area and diameter in 2005 between the two established sites (ANOVA, □=0.05, p<0.000) (Table 2, Figure 3). The average annual basal area change/ha was 0.1 m2 ha-1 yr-1 for both planted sites while it was 0.7 m2 ha-1 yr-1 for both established sites.

Comparing the planted sites, trees at Codet Road were growing significantly faster than those at Blacklick Creek, averaging 0.6 cm/yr (ANOVA, □=0.05, p<0.000). Blacklick Creek might have a lower growth rate because of greater herbivory; e.g. of 13 trees measured in one plot, 12 trees showed evidence of beaver damage. Another possible reason for the low growth at Blacklick Creek may be due to an incorrect estimation of the original DBH and height. If the actual DBH and height of the trees in 1994 were smaller than that estimated (0.6 cm and 1.3 m, respectively) the calculated growth rate would be an underestimate.

Individual tree species growth

At the established forest sites (Table 3), the tree with the highest annual growth in DBH was *Salix* sp. (willow) (1.5 cm/yr); its growth was significantly greater than 17 other species (ANOVA, □=0.05, p<0.000). *A. saccharinum* showed the greatest dominance, owing to the large size of these trees, and was followed in dominance by *Fraxinus pennsylvanica* (green ash) at Gahanna Woods and *Quercus*

Table 3 Growth in diameter and basal area, dominance, relative dominance, density and mean DBH of trees > 1.3m tall and 2.5 cm DBH at New Albany and Gahanna Woods measured in 20 plots at each site in 2004 and remeasured in 2005.

Species Name	Site	Mean annual growth in diameter (cm/yr)	Mean annual growth in basal area (cm^2/yr)	Dominance (cm^2/ha)	% Relative Dominance	Mean DBH in 2005 (cm)	Density (trees per ha)
Acer negundo	New Albany	0.0±0.0	0.6±0.6	2838	1.5	35.5±23.5	2.5
Acer rubrum	Gahanna	0.3±0.1	11.6±3.6	10737	3.5	21.4±2.5	28.4
	New Albany	0.3±0.0	15.0±3.1	40562	22	20.4±1.6	102.5
Acer saccharinum	Gahanna	0.3±0.0	20.9±3.0	129657	41.9	37.0±2.4	108.6
	New Albany	0.5±0.1	27.8±5.6	49855	27.0	32.4±3.5	50.6
Acer saccharum	Gahanna	0.5±0.1	4.9±1.9	487	0.2	6.9±1.6	11.1
	New Albany	0.1±0.1	0.9±0.7	103	0.1	5.9±2.1	3.7
Amelanchier sp.	Gahanna	0.0±0.0	0.0±0.0	6	0.0	2.8	1.2
Asimina triloba	Gahanna	0.3±0.0	1.9±0.1	1283	0.4	4.1±0.1	108.6
Carpinus caroliniana	Gahanna	0.1±0.0	1.1±0.2	1073	0.3	5.7±0.4	43.2
Carya laciniosa	New Albany	0.4±0.0	5.7±0.0	88	0.0	10.6	1.2
Carya ovata	Gahanna	0.3±0.1	11.3±4.2	5505	1.8	22.3±2.8	14.8
	New Albany	0.2±0.0	1.7±0.5	116	0.1	5.7±1.2	4.9
Celtis occidentalis	Gahanna	0.5±0.1	6.0±1.5	2296	0.7	8.5±1.6	28.4
Cornus florida	Gahanna	0.2±0.0	1.4±0.2	676	0.2	5.2±0.4	34.6
	New Albany	0.6±0.3	10.3±6.7	183	0.1	10.5±2.8	2.5
Crataegus sp.	Gahanna	0.3±0.1	2.5±1.1	228	0.1	5.6±1.3	8.6
	New Albany	0.1±0.1	0.3±0.3	51	0.0	4.5±0.9	3.7
Fagus grandifolia	Gahanna	0.2±0.0	4.5±1.0	22583	7.3	10.8±1.5	111.1
	New Albany	0.4±0.2	4.8±2.2	453	0.2	12.4±4.4	3.7
Fraxinus americana	Gahanna	0.6±0.3	54.7±29.3	7195	2.3	55.1±2.6	3.7
	New Albany	0.0±0.0	0.0±0.0	17	0.0	4.6	1.2
Fraxinus pennsylvanica	Gahanna	0.4±0.0	23.2±4.6	43053	13.9	30.4±3.9	45.7
	New Albany	0.4±0.1	10.6±2.5	17559	9.5	14.7±1.9	67.9
Gleditsia triacanthos	Gahanna	0.1±0.0	13.8±0.0	2743	0.9	59.1	1.2
Juglans nigra	Gahanna	0.4±0.1	31.5±10.3	17177	5.5	49.4±6.5	9.9
	New Albany	0.2±0.0	8.6±0.0	503	0.3	25.3	1.2
Lindera benzoin	Gahanna	0.3±0.1	1.2±0.5	58	0.0	3.4±0.3	7.4
Malus pumila	New Albany	0.0±0.0	0.0±0.0	71	0.0	9.5	1.2

Nyssa sylvatica	Gahanna	0.0±0.0	0.0±0.0	3536	1.1	67.1	1.2
	New Albany	0.0±0.0	0.9±0.6	866	0.5	12.0±4.4	6.2
Ostrya virginiana	Gahanna	0.3±0.0	2.8±0.3	3111	1.0	7.9±0.5	66.7
Populus deltoides	New Albany	0.5±0.1	37.3±9.4	5157	2.8	46.2±5.4	3.7
Prunus americana	New Albany	0.1±0.0	0.6±0.0	12	0.0	3.9	1.2
Prunus serotina	Gaha nna	0.3±0.0	10.0±2.0	29197	9.4	24.2±2.8	50.6
	New Albany	0.2±0.1	3.5±1.3	5883	3.2	14.0±1.6	34.6
Quercus alba	Gahanna	0.3±0.1	26.6±23.4	5279	1.7	47.3±33.5	2.5
Quercus bicolor	Gahanna	0.3±0.0	30.8±0.0	3349	1.1	65.3	1.2
	New Albany	0.3±0.0	1.7±0.0	11	0.0	3.7	1.2
Quercus imbricaria	Gahanna	1.2±0.0	75.5±0.0	1276	0.4	40.3	1.2
	New Albany	0.2±0.0	2.8±0.0	100	0.1	11.3	1.2
Quercus muehlenbergii	Gahanna	0.4±0.0	10.0±0.0	224	0.1	16.9	1.2
Quercus palustris	Gahanna	0.2±0.1	9.3±6.5	3867	1.2	39.3±7.0	3.7
	New Albany	0.5±0.0	18.4±2.7	41226	22.3	20.7±1.5	103.7
Quercus rubra	Gahanna	0.4±0.2	21.9±17.0	1936	0.6	31.9±14.5	2.5
	New Albany	0.3±0.1	7.7±1.7	7048	3.8	13.5±1.6	42.0
Quercus sp. hybrid	New Albany	0.3±0.0	4.0±0.0	65	0.0	9.1	1.2
Quercus velutina	New Albany	0.7±0.0	20.5±0.0	308	0.2	19.8	1.2
Salix sp.	New Albany	1.5±0.0	7.9±0.0	13	0.0	4.1	1.2
Sassafras albidum	Gahanna	0.1±0.1	5.1±5.0	3381	1.1	29.5±8.3	4.9
	New Albany	0.2±0.0	5.7±1.9	895	0.5	15.4±4.0	4.9
Ulmus americana	Gahanna	0.4±0.0	3.6±0.4	4187	1.4	7.2±0.5	93.8
	New Albany	0.3±0.0	2.8±0.3	9236	5.0	7.4±0.4	192.6
Ulmus rubra	Gahanna	0.3±0.0	4.4±0.5	5296	1.7	11.2±0.8	54.3
	New Albany	0.2±0.1	4.7±1.8	971	0.5	18.8±5.5	3.7
Viburnum prunifolium	Gahanna	0.3±0.1	1.9±0.5	187	0.1	4.2±0.5	14.8
	New Albany	0.3±0.1	2.1±0.4	273	0.1	4.1±0.3	23.5
Viburnum trilobum	New Albany	0.0±0.0	0.0±0.0	10	0.0	3.5	1.2

palustris (pin oak) at New Albany. The most abundant species at Gahanna Woods was *Fagus grandifolia* (American beech), while at New Albany, it was *Ulmus americana* (American elm).

At the planted tree sites (Table 4), only *Betula nigra* (river birch) and *Q. palustris* were planted at both sites. Both species appear to be growing better at Codet Road where *Q. palustris*' annual DBH growth was approximately double that at Blacklick Creek.

At Codet Road, *F. pennsylvanica* was both the most dominant and abundant planted species, and had significantly greater annual DBH growth than 5 out of the 7 planted species (Anova, □=0.05, $p<0.000$).

At Blacklick Creek, *Quercus bicolor* (swamp white oak) was the most abundant planted species. *Platanus occidentalis* (sycamore) was the most dominant and the second most abundant species. It had the greatest growth in height (0.4 m/yr) of all the planted species and significantly greater growth in DBH/yr, basal area/yr and total basal

Table 4 Annual growth in diameter, basal area, height and current diameter of trees with s.e., dominance, relative dominance, density of trees > 1.3m tall at Blacklick Creek and Codet Road. Tree data were previously recorded in 1998 for Blacklick Creek and in 1992 for Codet Road and the same plots were revisited in 2005. Dominance is total basal area in 2005, while % Relative Dominance is Dominance/Total Dominance.

Species Name	Site	Δ diameter (cm/yr)	Δ basal area (cm^2/yr)	Δ height (m/yr)	Dominance	%Relative dominance	Mean DBH in 2005 (cm)	Density (trees/ha)
Acer rubrum	Codet Rd	0.6±0.3	8.4±6.3	0.2±0.1	676	4.3	9.3±3.4	6.4
Acer saccharinum	Codet Rd	0.7±0.1	9.4±2.3	0.3±0.1	2421	15.4	11.8±1.1	20.2
Betula nigra	Codet Rd	0.5±0.0	3.3±0.3	0.3±0.1	1188	7.5	7.3±0.3	28.7
	Blacklick	0.4±0.0	2.3±0.4	0.3±0.0	433	9.2	5.3±0.5	27.9
Crataegus sp.	Codet Rd	0.2±0.0	1.4±0.2	0.2±0.2	551	3.5	4.8±0.3	28.7
Fraxinus pennsylvanica	Codet Rd	0.9±0.1	11.5±1.0	0.3±0.1	5045	32.0	13.3±0.7	35.1
Liquidambar styraciflua	Codet Rd	0.5±0.0	4.9±0.4	0.3±0.0	1999	12.7	8.9±0.4	31.9
Platanus occidentalis	Blacklick	0.7±0.1	5.8±1.2	0.4±0.2	2227	46.8	7.8±0.8	57.4
Quercus bicolor	Blacklick	0.4±0.0	1.9±0.1	0.2±0.0	1776	37.8	5.0±0.2	134.4
Quercus michauxii	Blacklick	0.2±0.0	0.6±0.1	0.2±0.1	19	0.4	2.9	1.6
Quercus palustris	Codet Rd	0.8±0.0	9.3±0.8	0.3±0.1	3874	24.6	12.2±0.6	33.0
	Blacklick	0.3±0.0	1.4±0.2	0.2±0.2	269	5.7	3.7±0.5	31.1

area than *B. nigra* and all 3 planted oak species (ANOVA, □=0.05, p<0.000.).

The planted species with the lowest growth was *Quercus michauxii* (swamp chestnut oak) at Blacklick Creek with annual radial and basal growth of 0.1 cm/yr and 0.3 cm2/yr, respectively and annual height increase of 0.1 m/yr. *Nyssa sylvatica* (black gum) had the lowest growth at Codet Road with increases of 0.1 cm DBH/yr and 0.2 cm2/yr basal area/yr and <0.01 m/yr height.

Quercus palustris was the only species found in all four sites and that was planted at the planted sites (Tables 3 and 4). The annual growth in DBH/yr of Quercus palustris was highest at Codet Road. New Albany's *Quercus palustris* trees showed the greatest growth in basal area per yr.

Tree growth and elevation

Tree growth in each plot was correlated to the elevation at the center of the tree plots at each site. Figure 4 illustrates the results from Codet Road and Blacklick Creek. There is a weak pattern where the mid-range elevations had the greatest growth, although the variation within plots and between plots was high at Codet Road. Figure 5 shows the results from Gahanna Woods and New Albany. Here the pattern shows more growth in the lower elevations, although variation was again high.

Comparison of tree growth model with field results

Table 5 compares the predicted values of DBH from the tree model (Niswander and Mitsch, 1995) and height from Botkin's (1993) optimum tree growth equation with actual values measured in field at Codet Road in 2005. Predicted tree DBH was estimated from the graph of the output from the Niswander model (Niswander and Mitsch, 1995). The mean DBH measured in the field was less than that predicted in 5 of the 8 species, while the model accurately predicted the growth of *A. saccharinum* and *B. nigra* to within 10% of field data. *L. styraciflua*'s growth was higher than that predicted by the model. In the model *L. styraciflua* and *B. nigra* were predicted to grow at one-half their maximum rates because they were at the edge of their northern range, but this adjustment may not have been necessary for *L. styraciflua*, as it grew better than expected. The model greatly overestimated DBH for *A. rubrum*, *C. viridis* and *N. sylvatica*. *N. sylvatica* had very poor growth and survival at Codet Road. As with *B. nigra*, this species may need to have an adjustment in its growth rate made in the model for the cold winter climate in Ohio. The survival of *A. rubrum* (23%) was also poor at Codet Road for unknown reasons. Overall, the model predictions of DBH were 28% higher than the mean field measurements.

The Botkin tree growth equation predicted the height of 4 species (*A. rubrum, F. pennsylvanica, N. sylvatica* and *Q. palustris*) to within 10% of field measurements. It was most off the mark on A. saccharinum and B. nigra. Overall, the model predictions of height were 12% lower than the actual mean field measurements.

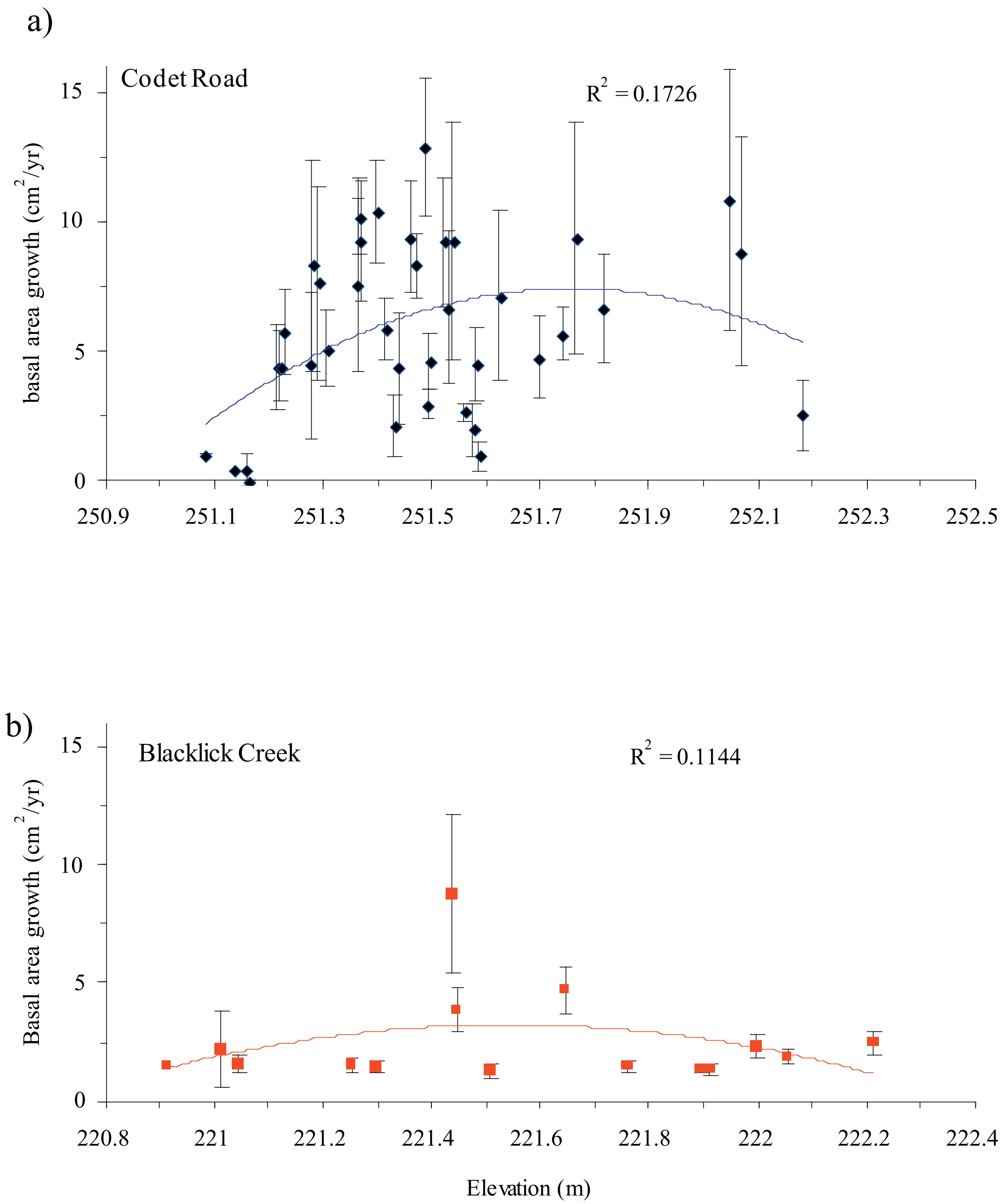


Figure 4   Mean annual increase in tree basal area vs. elevation at planted wetlands: a) Codet Road and b) Blacklick Creek. Values are mean increase in basal area/yr ± s.e. with a curve fitted to points (2nd order polynomial

Table 5 Predicted and actual diameter at breast height (DBH) and height of planted tree species at the Codet Road wetland. Predicted DBH from tree growth model (Niswander and Mitsch 1995) and height from Botkin (1993). Actual DBH and height are means of trees measured in field in 2005.

Species	Actual DBH 2005 (cm)	Predicted DBH 2005 (cm)	Difference between actual & predicted DBH (cm)	Difference in DBH, %	2005 Actual height (m)	2005 Pred. height (m)	Difference between actual & Pred. height (m)	Difference in height %
Acer rubrum	8.1	15	-6.9	85	4.8	5.0	-0.2	4
Acer saccharinum	11.8	11	0.8	7	6.2	8.3	-2.1	34
Betula nigra	7.3	7	0.3	4	6.0	3.8	2.2	37
Crataegus viridis	4.8	10.5	-5.7	119	4.0	3.0	1.0	25
Fraxinus pennsylvanica	13.0	17	-4	31	6.6	6.7	-.1	2
Liquidambar styraciflua	8.6	5	3.6	42	5.6	4.6	0.9	16
Nyssa sylvatica	1.9	11	-9.1	478	2.3	2.3	0.0	0
Quercus palustris	12.2	21	-8.8	72	5.9	6.3	0.4	7
Average	9.5	12.2	-2.7	28	5.7	5	0.7	12

Survival of trees planted

Of the 270 trees that had previously been measured in 1992 at Codet Road (Niswander and Mitsch, 1995), 178 (66%) were found again in 2005. The rest were assumed to have died, resulting in 34% mortality (Table 6). *N. sylvatica* had the highest mortality and the smallest increase in growth (Table 4) while *Q. palustris* had the lowest mortality and one of the highest increases in DBH.

At Blacklick Creek, trees found in plots in 2005 were compared with the June 1998 consultants report (LAW Engineering and Environmental Services 1998) to compute the survival since 1998 (Table 7). Of the 259 planted trees identified in the plots in 1998, 71% (185 trees) survived. *Q. michauxii* had the greatest mortality at 60%, followed by *B. nigra* with 30%. Overall mortality was 29% within the tree plots measured. Yearly tree mortality at Blacklick Creek (29% over 11 years = 2.6% per year) is equal the yearly tree mortality at Codet Road (34% over 13 years = 2.6% per year).

Volunteer trees

At Codet Road, 578 trees greater than 1.3 m (including those less than 2.5 cm DBH) were measured in 2005; 356 of those trees had volunteered (in other words these trees were not recorded in plots in 1992), resulting in a density of volunteer trees of 379 trees/ha (Table 8). Over 50% of the new trees were *F. pennsylvanica* while 23 % were *A. negundo* (box elder.) Other new volunteer species included *Catalpa* sp., *Populus deltoides* (eastern cottonwood), *Prunus serotina* (black cherry) and *Salix* sp. Many *F. pennsylvanica* trees clustered close to the water near the outlet weir area, suggesting the seeds were brought in by hydrochory.

F. pennsylvanica was also one of the planted species at Codet Road. Planting did give this species a head start, as the mean DBH of all planted *F. pennsylvanica* trees was 13 cm while for the volunteer *F. pennsylvanica* trees it was 2.6 cm.

At Blacklick Creek, 441 trees were measured; 267 of those trees were not in the plots in 1998 (Table 8). Twenty-six percent of the volunteer trees were *Acer negundo* and 26% were *P. deltoides*; *F. pennsylvanica* made up 23%. Other new volunteer tree species included *Gleditsia triacanthos* (honey locust), *Juglans nigra* (black walnut), *Juniperus virginiana* (eastern redcedar), and *Robinia pseudoacacia* (black locust). At Blacklick Creek, the tree plot closest to (about 30 m from) the existing bottomland forest had the greatest number of trees (94) and the greatest number of species (9).

Tree species richness and diversity

Gahanna Woods and New Albany, the sites with established forests, both had similar species richness (29 species). Gahanna Woods provides a reference site of a mature forested wetland and had the highest species diversity (H'=2.7) while New Albany had an H' of 2.1. Blacklick Creek and Codet Road were the planted sites and had lower species richness (12 and 13 species) and diversity (H'=2.1 and 2.0), respectively. Eight tree species were planted at Codet Road while only five were planted at Blacklick Creek. The higher number of volunteer species at Blacklick Creek may indicate that Blacklick Creek has a greater seed source from the floodwaters of Blacklick Creek and the bottomland forest adjacent to it.

Table 6 Estimated mortality of planted trees at Codet Road. Plots where trees were found in 1992 were revisited in 2005. If a tree was not found in the plot, it was assumed to have died.

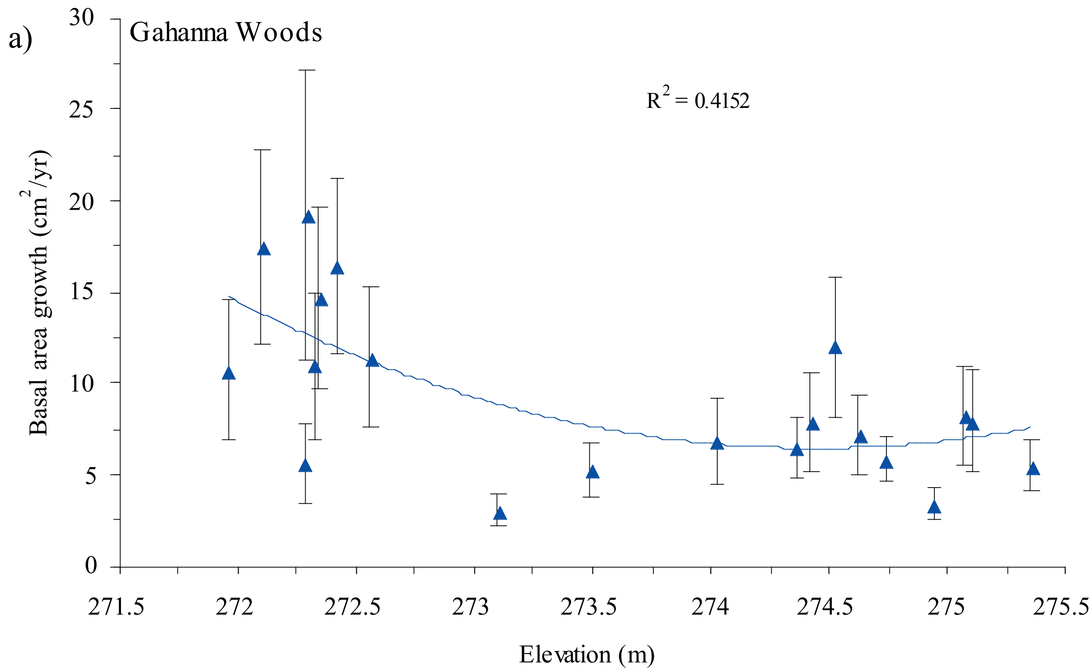
Species	# trees found in 1992	# trees found in 2005 > 1.3 m in height	Mortality (%)
Acer rubrum	30	7	77
Acer saccharinum	28	19	32
Betula nigra	32	27	16
Crataegus viridis	39	27	31
Fraxinus pennsylvanica	44	34	23
Liquidambar styraciflua	37	31	16
Nyssa sylvatica	25	2	92
Quercus palustris	35	31	11
Total	270	178	34

Table 7 Estimated mortality of planted trees at Blacklick Creek. Plots where trees were found in 1998 were revisited in 2005. If a tree was not found in the plot, it was assumed to have died. Column labeled "additional trees found" are planted tree less than 1.3 meter so not measured for growth, only noted for survival.

Species	# trees found in 1998	# trees found in 2005 >1.3 m in height	# trees found in 2005 <1.3 m in height	Mortality (%)
Betula nigra	33	23	0	30
Platanus occidentalis	38	35	0	8
Quercus bicolor	120	92	6	18
Quercus michauxii	20	5	3	60
Quercus palustris/shumardii	48	19	2	56
Totals	259	174	11	29

Table 8 Comparison of density of all trees found in tree plots with density of volunteer trees by site as well as the mean dbh of volunteer trees. Trees were > 1.3 m tall.

Wetlands	Density of all trees/ha	Density of volunteer trees/ha	Mean dbh of volunteer trees (cm)
Blacklick Creek	723	437	4.1 ± 0.2
Codet Road	615	379	2.7 ± 0.1
Average	669	408	3.3 ± 0.1



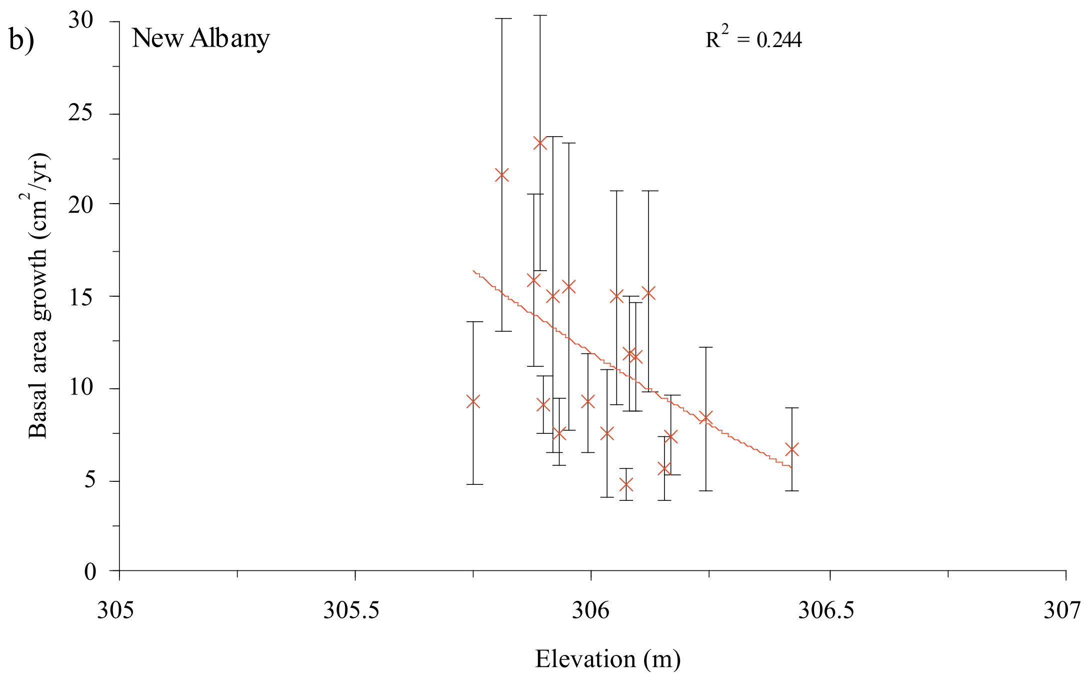


Figure 5 Mean annual increase in tree basal vs. elevation at center of plots of reference wetlands a) Gahanna Woods and b) New Albany. Values are mean increase in basal area (cm2/yr) ± s.e. at each elevation. Fitted curve to points (2nd order polynomial).

Hydrology of the planted tree sites

Codet Road and Blacklick Creek, the two planted wetlands, had at least one deepwater (>50 cm) basin that held surface water continuously (Figures 2a, c). Blacklick Creek's pond averaged a water depth of 1 m while Codet Road's average water depth was about half of that. While the gages were set at deep points in the basins, they were not set at the deepest point in either wetland and so they do not reflect maximum depths. Blacklick Creek also had a greater maximum gage height of 1.8 m compared to 1 m for Codet Road and a greater range between minimum and maximum values of 1.4 m compared to Codet Road's range of 0.6 m.

Hydrologic pulsing

Although the two planted wetlands have their primary water source as streams, their wetland hydrographs display decidedly different pulsing patterns (Figure 6).

The pond water level at Blacklick Creek (Figure 6a) shows a seasonally decreasing trend from spring through fall with the exception of several flood events where the

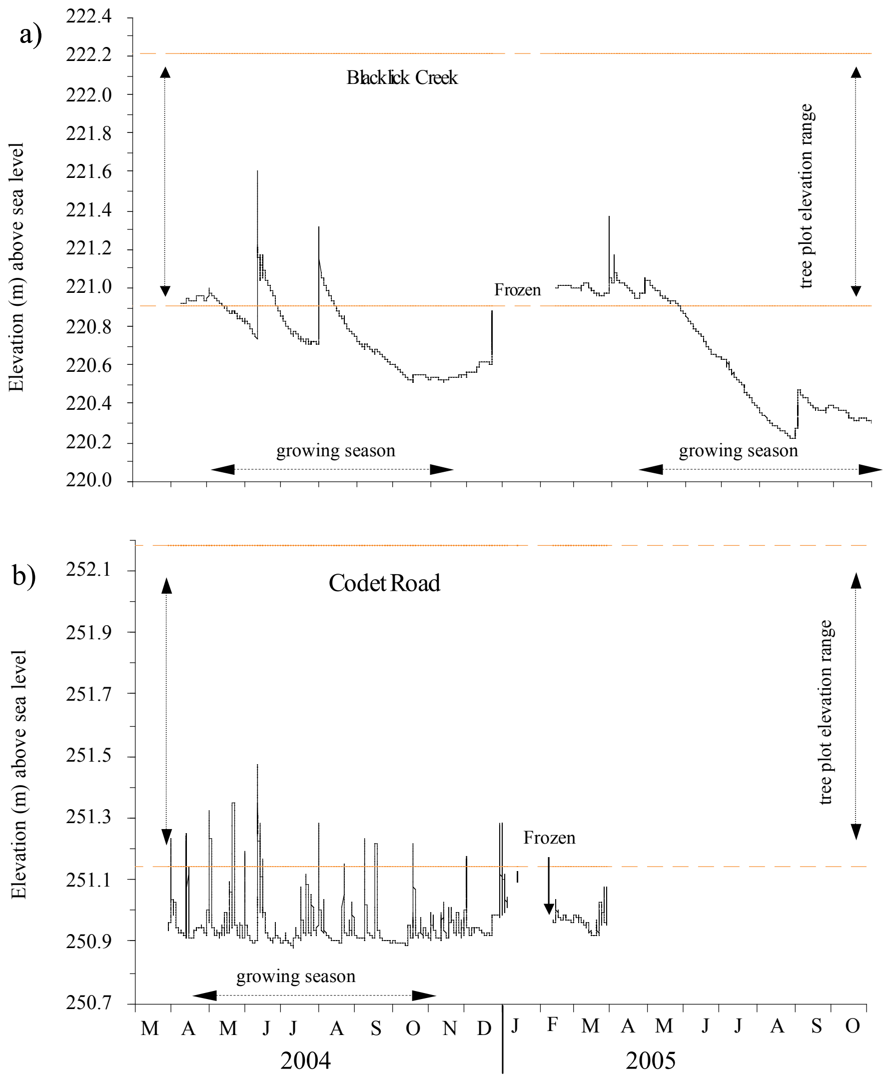


Figure 6 Hydrographs of a) Blacklick Creek's pond and b) Codet Road's south basin. Vertical arrows indicate range of elevations where tree plots were located. Horizontal arrows indicate growing season. "Frozen" indicates when float was frozen in stilling well so no data were recorded.

water level peaks sharply as water from Blacklick Creek floods over the inlet weir into the wetland.

The Codet Road wetland's hydrograph (Figure 6b) shows hydrologic pulsing with rapid changes in flow and stage during storm events when the water can rise over 10-50 cm in a matter of hours. There is no weir constricting Codet Road's inflow so it responds rapidly to changes in stream flow.

Comparing the hydrologic pulsing between Blacklick Creek and Codet Road, Codet Road has a greater number of pulses (34) from March 2004 to March 2005 with the duration of pulses averaging about 4 days. Twenty-three of the pulses were within the growing season. Blacklick Creek had only 3 pulses per year and the duration of its pulses was longer, averaging almost a month. The amplitude of the pulses was greater at Blacklick Creek since a large volume of water enters the wetland when Blacklick Creek is high enough to flood over the weir into the wetland. Only two pulses at Blacklick Creek were within the growing season.

Are the trees planted in a wetland?

Figures 6 a & b have arrows indicating the elevation range where trees were planted at Blacklick Creek and Codet Road. At Codet Road, water floods into the elevations where the trees are planted only for short periods during peak floods and only in the lower tree zone elevations.

At Blacklick Creek, Figure 6a suggests that there would be periodic flooding of the lower elevations in the tree zone, with longer periods of standing water in the winter and spring.

Discussion

Tree growth

This study found differences in the growth rates of the trees based on a) site; b) size; c) tree species; and, to some extent, d) elevation of the tree on the floodplain.

Tree growth (diameter increase/yr) was significantly higher in planted sites, about double the growth of trees in the established forest sites. The planted forests' annual growth in diameter was the same as that found in a planted Maryland mitigation wetland (Perry et al., 1996). The Blacklick Creek planted site may have had less growth due to greater herbivory.

The established forest growth was similar to the growth of trees at a central Ohio riparian site (Dudek et al., 1998). The established forests may have slower growth due to the fact that as trees become larger, their growth rate declines (Spurr and Barnes, 1973). However, the established sites produced about five times more tree basal area increase per yr as they contained larger-sized trees. Tree growth in the New Albany established forest site was comparable to the reference site, although density, total basal area and diversity were less.

Our reference forested wetland site (Gahanna Woods) had a total basal area of 38 m^2/ha, which was comparable to total basal area basal areas of 31 and 35 m^2/ha found in an old growth forest in southeastern Ohio dominated by oaks and maples (McCarthy et al., 2001). The basal area change of 0.7 $m^2\ ha^{-1}\ yr^{-1}$ at both established sites is greater than that reported (0.5 $m^2\ ha^{-1}\ yr^{-1}$) for an old-growth hardwood forest is southern IL (Zaczek et al., 2002). The planted sites' total basal area was much less, around 2 m^2/ha, with a basal area change of only 0.1 $m^2\ ha^{-1}\ yr^{-1}$. As a contrast between planted and unplanted sites, the total basal area found in an unplanted 16-years-abandoned field in Louisiana which was converting to a bottomland forest was 0.7 $m^2\ ha^{-1}$ (Battaglia et al., 2002) which was less than this study's planted sites.

The planted sites had less diversity with 5-9 tree species planted and 12-13 total species found, compared to 29 species found in our reference wetland. *F. pennsylvanica*, *Q. palustris*, and *A. saccharinum* were important tree species at the established sites as well as the planted sites. *F. pennsylvanica* had significantly greater growth in DBH and basal area than other planted species and was the most dominant and abundant tree at one site, composing over 50% of the volunteer trees. *A. saccharinum* was the dominant tree at both established sites while *F. pennsylvanica* was the next most dominant at Gahanna Woods and *Q. palustris* was the 2nd most dominant and abundant tree at New Albany. At an abandoned field site restoring naturally to a bottomland hardwood forest in Louisiana, *F. pennsylvanica* was found to be the most abundant and dominant tree in terms of basal area (Battaglia et al., 2002).

Simulated DBH obtained from the Niswander and Mitsch (1995) tree growth model compared well with field DBH for *Acer saccharinum*. Using Niswander and Mitsch's tree growth model output for *A. saccharinum*, it would take approximately 44 years for the planted *A. saccharinum* trees at Codet Road to match the mean DBH of the trees at our reference site Gahanna Woods.

Tree species have an individualistic response to elevation (Bledsoe and Shear, 2000; Keeland et al., 1997). *P. occidentalis* had its greatest growth at lower elevations in Blacklick Creek. This species, found in floodplains and stream banks where there is local seepage, does not tolerate inundation for long periods (Braun, 1989). Alternatively, in the south, *F. pennsylvanica*, which is highly tolerant of flooding, had 80% greater growth when the ground was inundated from spring through August (Broadfoot and Williston, 1973). At the planted tree sites in this study, there appeared to be greater growth in the mid-elevations in each site, although variation between plots was high and the correlation was not strong. The high rates of growth at mid-elevations may reflect an optimum combination of stress and subsidy for tree species at these sites (Megonigal et al., 1997). A study of tree response to elevation in Australia found a similar pattern of total basal area being greatest at the center of the elevation gradient (Bowman and McDonough, 1991). At the established sites, the effect of elevation on growth was different. Here basal area growth was greater in the lower elevations, where there were generally fewer trees in the plots, but the trees were larger and included species such as *A. saccharinum* and *Q. palustris* which tolerant flooding. A study of the effect of flooding on oak seedlings also found that the trees grew better at lower elevations where drought and competition were less of a limiting factor (Burkett et al., 2005).

Elevation, flooding duration and depth and forest productivity

Small differences in elevation can have a great effect on the amount of flooding at a site, making the design and restoration of forested wetlands very challenging (Bledsoe and Shear, 2000). As newly planted trees are especially susceptible to flooding stress, water levels in newly constructed wetland may need to be lower initially in order for the woody plants to establish themselves (Niswander and Mitsch, 1995).

Surface water flooding does not necessarily predict productivity (Mitsch et al., 1991). A study (Megonigal et al., 1997) testing the hypothesis that periodically flooded forests would have greater productivity (Odum, 1979) did not find results to support this theory. Megonigal et al. (1997) supported Mitsch and Rust's model (1984) that flooding's benefits of water and nutrients may be cancelled by stress from anaerobic soils and drought. The season of flooding (Crawford, 2003), even the weekly water level changes (Keeland and Sharitz, 1997), were found to be important rather that frequency of flooding (Robertson et al., 2001).

Establishing appropriate hydrology for created and restored wetlands

The success of wetland creation and restoration projects depends on the ability to restore or establish and maintain proper wetland hydrology (Hammer, 1992; Mitsch and Jorgensen, 2004). Fluctuating water levels with seasonal highs in winter and spring (in Eastern and central USA), and peaks in response to storm events are a natural feature in wetlands (Mitsch and Jorgensen, 2004). Gentle slopes (6:1 or greater) on constructed basins are recommended as they maximize the area for emergent vegetation (Mitsch and Jorgensen, 2004).

The two planted tree sites, Blacklick Creek and Codet Road, had hydrologic patterns that reflected their different water sources, their connectivity to those sources, and the size of their watershed. Codet Road wetland's main water source is a channelized stream that, coupled with its small watershed, creates a flashy hydroperiod with water levels that rise and fall rapidly in response to precipitation events. The south basin has an average depth of about 50 cm that, along with the gently sloping sides, enables it to supports extensive emergent and submergent vegetation zones.

Despite its name, Blacklick Creek is a large stream and has much a greater watershed (156 km^2) than Codet Road (2.6 km^2). The water levels at the Blacklick Creek wetland reflect conditions over the entire watershed and respond more to seasonal effects such as heavy spring and fall rains where water floods into the wetland than to local precipitation events. This causes the water levels to be less flashy. Flood events replenish water in the pond and raise the groundwater levels in the planted forest area for several days. Water is retained in the pond year round, at a depth of around 1m, and its steep banks do not permit emergent vegetation. Another study found this site to have the steepest bank of any mitigation wetland in Ohio (Fennessy, 1997). This site is an example of mitigation wetlands created to have large areas of open water and steep slopes (to maximize area) and a permanent hydroperiod with minimal water level fluctuation (to minimize the risk of not meeting hydrology requirements in dry years) (Porej, 2003).

Codet Road's hydrology follows the pulsing hydrology of a natural wetland. Productivity has been found to be highest in pulsing hydroperiods (Mitsch et al., 1991) and in free-flowing sites (Johansson and Nilsson, 2002). Codet Road's planted trees showed greater growth in DBH and basal area/yr than Blacklick Creek, which had only a few pulses per year.

Planting vs. colonization

Trees were planted at two of our non-forested sites in order to accelerate the development of a forested wetland. Planted F. pennsylvanica had a mean DBH over 4 times greater than the naturally colonizing F. pennsylvanica. At the two planted tree sites, mortality was 34% and 29%, with an average loss of around 3% per yr. This is in the range of another study of forested mitigation wetlands (Perry et al., 1997) which found 35% tree mortality.

What effect initial planting has on the wetland's future trajectory is largely unknown (Mitsch and Jorgensen, 2004). The unplanted system may end up the same as the planted given enough time. But initial planting may have a effect on ecosystem functioning even years after planting. In one study comparing ecosystem functions of a paired set of wetlands, one naturally colonized wetland and one herbaceously-planted wetland, differences were found in water quality and carbon accumulation between the wetlands (Mitsch et al., 2005). Even 10 years after planting, the planted wetland continued to be more diverse while the unplanted wetland was more productive but more susceptible to stress.

Some species such as oaks (*Quercus*) may need to be planted as they invade old-field sites at a slower rate that other species (Allen, 1997). Most tree species volunteer 60 m or less from a mature forest (Allen, 1997; Brown et al., 1992). Seed dispersal has been found to decrease exponentially as the distance increased from the edge of the forest (Brown et al., 1992). In the current study, the plot at Blacklick Creek closest to an existing bottomland forest had the highest density and diversity, which confirms the importance of being near an existing forest for seed dispersal. Water dispersal of seeds could also be important if headwater wetlands are intact (Brown et al., 1992). At the Codet Road site, green ash trees volunteered close to the water's edge near the outlet weir, suggesting that the tree seeds were brought in by hydrochory.

Trees need to be chosen carefully to match a site's hydrology (McLeod et al., 2000). The planted species with the poorest growth—*Quercus michauxii* and *Nyssa sylvatica*—are both classified as weakly tolerant of flooding, able to survive saturated or flooded soils for a few days to a few weeks during the growing season (McKnight et al., 1981). The reason for their poor growth and survival may be due to the combined stresses of too much water and too cold a climate as both of these species generally have a more southerly range (Braun, 1989; Dirr 1998).

Conclusions

Comparing each sites tree measurements provides insight into their future trajectory and advantages of each site:

1) The site with the pulsing hydrology provided the greatest annual growth in DBH. A pulsing hydrology brings in nutrients and replenishes the water table, while not subjecting the trees to lengthy inundation, maximizing this site's tree growth and accelerating its development of a closed canopy forest.

2) The site constructed in an existing forest had the greatest annual growth in tree basal area, illustrating the high productivity and function provided by an existing forest. The Niswander and Mitsch (1995) tree growth model estimated it would take 44 years for *Acer saccharinum* trees at the site with the highest growth in DBH/yr to reach the average DBH of *Acer saccharinum* trees at the reference site. Using tree growth models to predict tree growth and height gives restoration managers some guidance as to how long trees will need to grow to match the size of trees at a natural site.

3) The site constructed next to an existing bottomland forest exhibited the greatest density of trees and number of volunteer trees. The existing forest provides a ready seed source for new trees and can enhance a site's species diversity.

Planting accelerates development compared to natural colonization as the mean DBH of planted *Fraxinus pennsylvanica* was 13 cm while the volunteer DBH was 2.6 cm. The need to plant species suited to the site and to the climate is revealed by the low growth and great mortality of *Quercus michauxii* and *Nyssa sylvatica* at the planted sites.

The reference site provides a good example of what is lost when forested wetlands are destroyed, as the reference site had the greatest density, total basal area, mean DBH, and species diversity of all the sites.

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